

Prospects for
Electroweak Physics
during Run II of
the Tevatron

W, Z Bosons &
Top Quark

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Outline

* Top Quark Physics

- Production cross section, dynamics
- Branching ratios, rare decays
- t-W-b vertex
- Top quark width
- Top quark mass

* Gauge Boson Properties

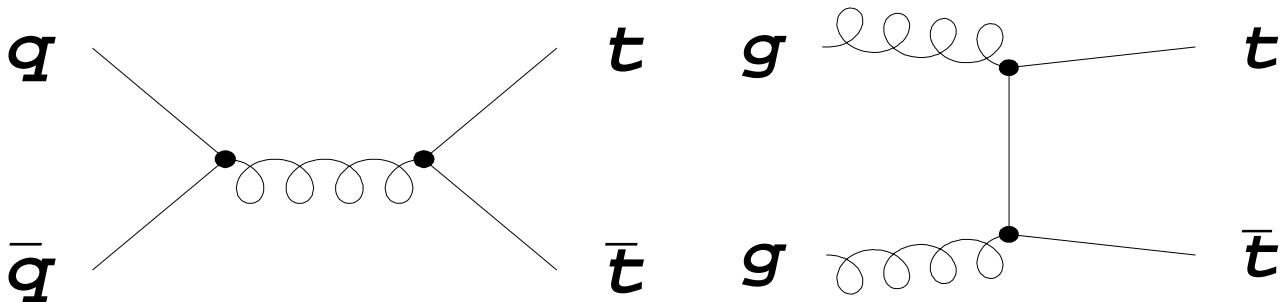
- W boson mass
- W boson width
- W and Z asymmetries
- Trilinear gauge boson couplings

t̄t Event Yields

- * tt production cross section increases by ~40% for \sqrt{s} change from 1.8 to 2 TeV .
- * For $m_t=175$ GeV

$$\sigma(pp \rightarrow tt + X) \approx 7.5 \text{ pb}$$

(Berger and Contoponagos)



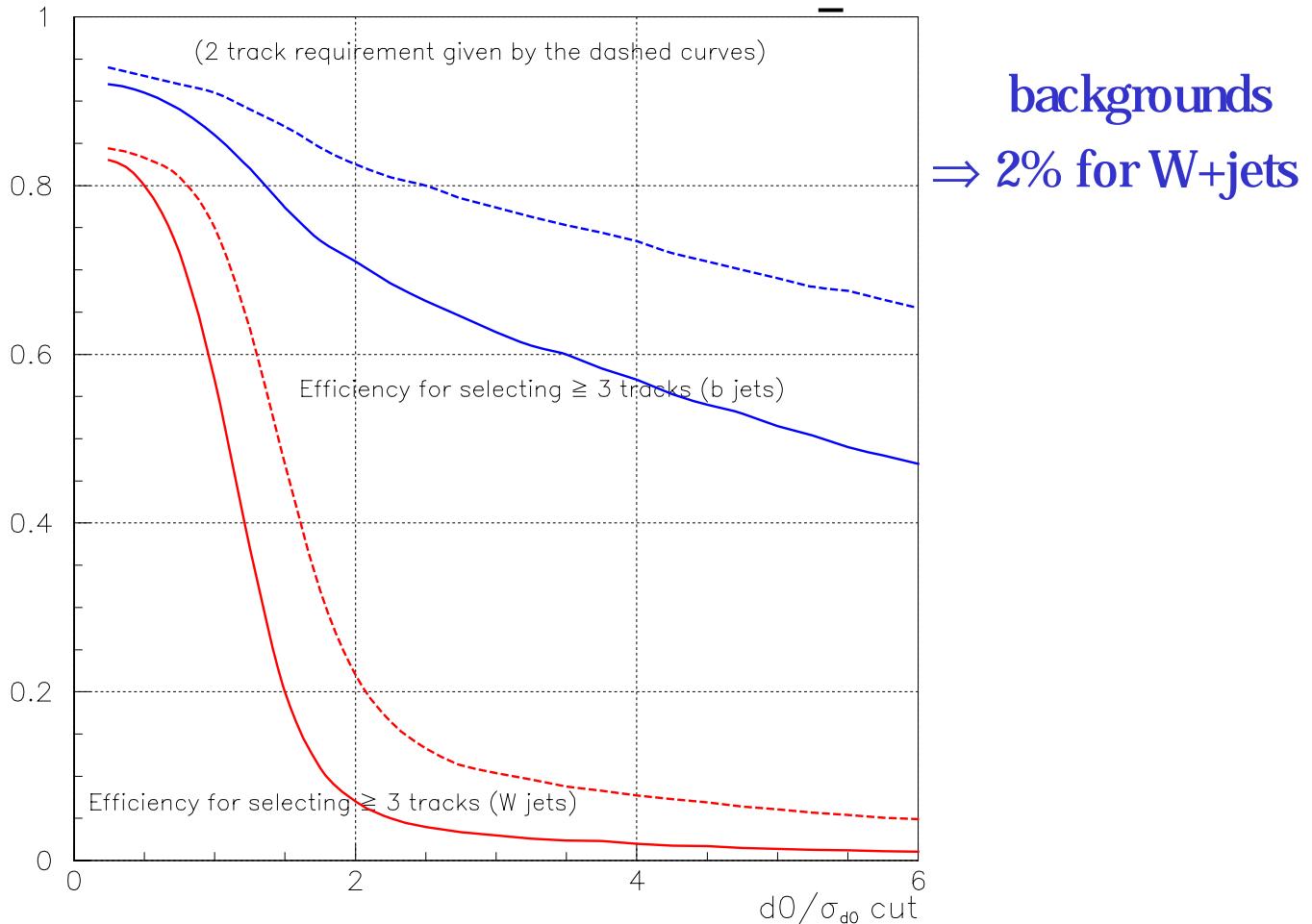
- * Expected event yields for 2 fb^{-1}

| channel | # events | S:B |
|----------------------------------|----------|------|
| dilepton | 200 | 5:1 |
| lepton+ ≥ 4 jets | 1,800 | |
| lepton+ ≥ 3 jets/b-tag | 1,400 | 3:1 |
| lepton+ ≥ 4 jets/dbl b-tags | 300 | 12:1 |

(Note: b-tag \Rightarrow displaced vertex and semileptonic tags)

b-tagging in Top Events

- * Displaced vertex tagging
 - ~50 - 60 % efficiency for b-jets in tt event



- * Soft lepton tagging:
 - tag b-jet via its semileptonic decay $b \rightarrow \mu/e + X$
 - Soft e-tag $\Rightarrow E/\not{p}$ helps identify soft-e inside b-jet
 - Soft μ -tag \Rightarrow extended to forward region,
- * Combined b-tagging efficiency $\Rightarrow \geq 60 - 70\%$
 - (at least one jet is tagged)

Cross Sections

- * Precision on top cross section ~8%
 - Statistical Error : 4%
 - Systematic errors assumed to scale with statistics
 - errors from backgrounds: decrease with increased statistics of control samples (2%)
 - jet energy scale (2%)
 - Radiation : Initial state (2%), Final state (1%)
 - Limiting Factors ?
 - error on geometric and kinematic acceptances depend on differences between generators (Pythia, Herwig, Isajet) (4%)
 - luminosity error (4%),

Top Quark Mass

- * Lepton+jets channel
- * $m_t = 173.3 \pm 5.6$ (stat) ± 5.5 (sys) GeV **DØ**
 $= 175.9 \pm 4.8$ (stat) ± 5.3 (sys) GeV **CDF**

- * uncertainties:

| | <i>Run I (DØ)</i> | <i>Run II</i> |
|-------------------|--------------------------|----------------------|
| • statistics | 5.6 | 1.3 GeV |
| • jet p_T scale | 4.0 | 1.5 GeV |
| • MC generator | 3.1 | 2.0 GeV (limit??) |
| • MC model | 1.6 | 0.5 GeV |
| • fit procedure | 1.3 | 0 |

- * Run II expectations:
 - calibrate jet p_T scale using data:
 - $Z + \text{jet}$, $\gamma + \text{jet}$, $W \rightarrow jj$, $Z \rightarrow bb$
 - double b-tag \Rightarrow reduce combinatorics
 - constrain MC model using data
- * Total uncertainty $\approx 2\text{-}3$ GeV

t̄t Resonances

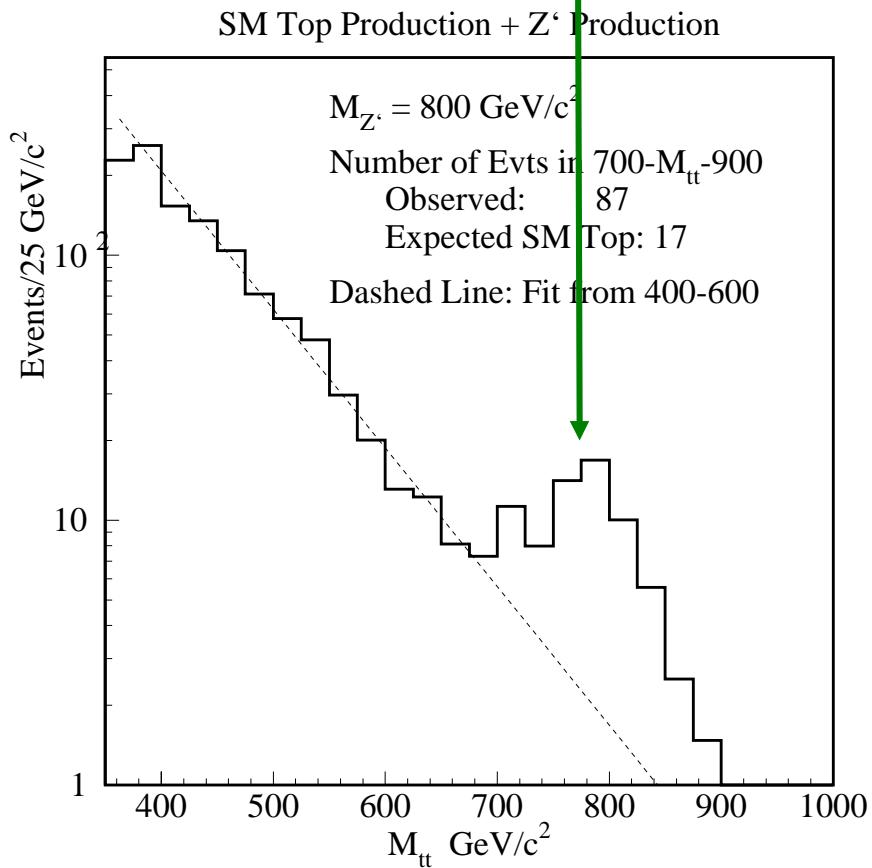
* Search for tt resonances

- look for peak in m_{tt} distribution (e.g. topcolor Z')
- Limits from Run I ~ 500 GeV
- Limits from Run II could be ~ 1 TeV
- expect

17 from tt

70 from Z'

$700 < m_{tt} < 900$

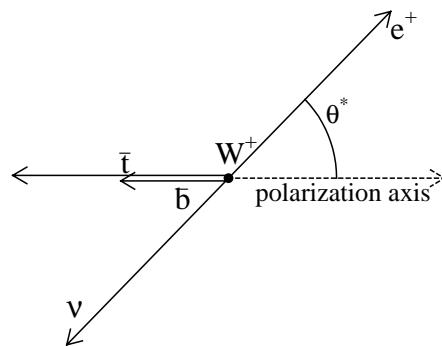


t-W-b Vertex

- * Top quarks decay before they hadronize

- * polarization of W :
$$\frac{W_{long}}{W_{left}} = 0.5 \left(\frac{m_t}{m_W} \right)^2$$

- * non-standard top couplings may result in different W polarization



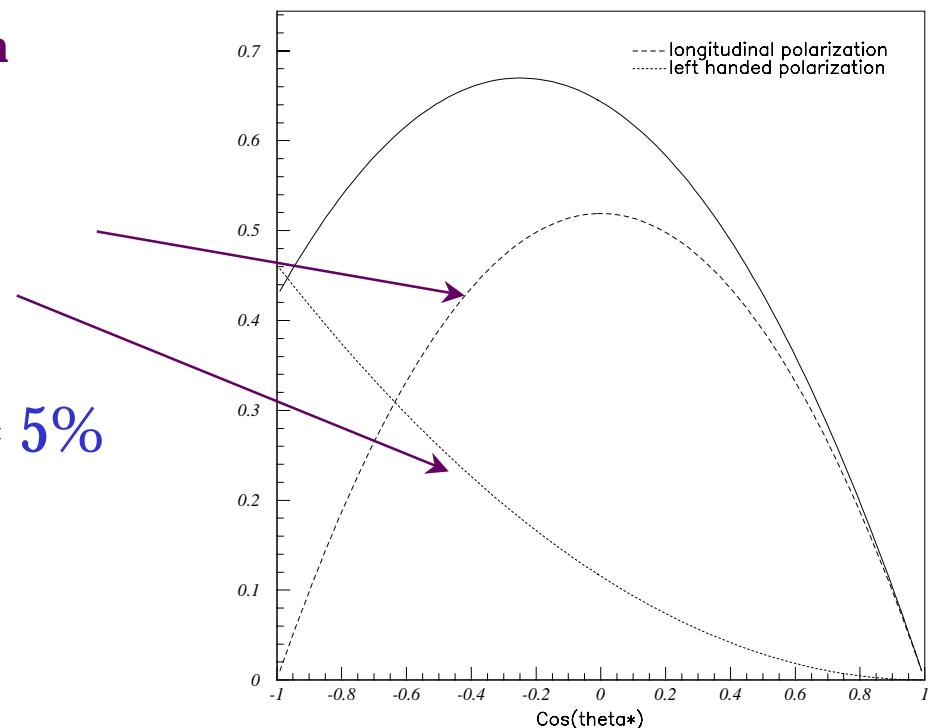
Charged lepton p_T &
angular distribution



Longitudinal W vs.
Left Handed W's

$\delta B(t \rightarrow bW_{long}) \approx 5\%$

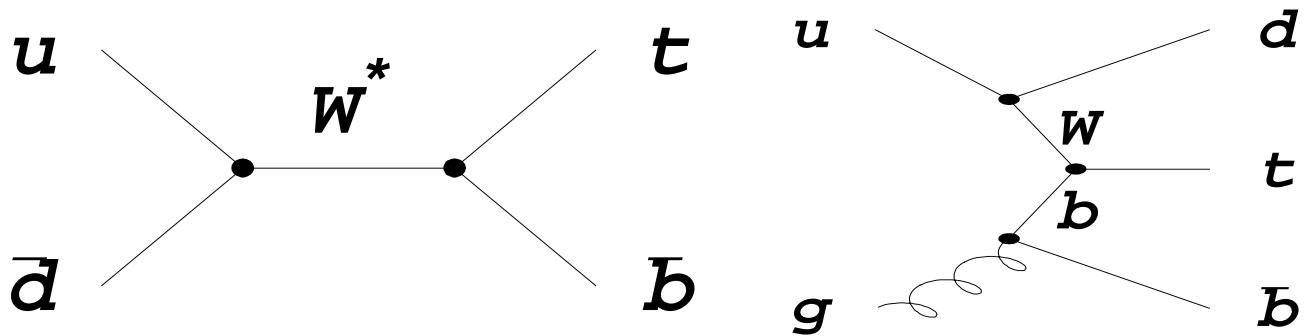
mtop = 170 GeV



t̄t Spin Correlation

- * Significant asymmetry exists in same-spin vs. opposite-spin top quark pairs
 - expect 70% t̄t opposite helicity
- * Polarization state is transmitted to the angular distribution of decay products.
- * Non-zero measurement
 - Confirms top quark spin = 1/2
 - ⇒ set lower limit on top quark width
 - ⇒ probe presence of non-standard interactions
- * Use charged lepton, lightest quark angular distributions in lepton+jet events
 - difficult to identify the down quark jet.
- * OR, angular correlation of leptons in dilepton events.
 - Possible to measure $\approx 3\sigma$ effect in 2fb^{-1}

Single Top Production



$$\sigma(pp \rightarrow Wg \rightarrow t + X) = 2.4 \pm 0.12 \text{ pb}$$

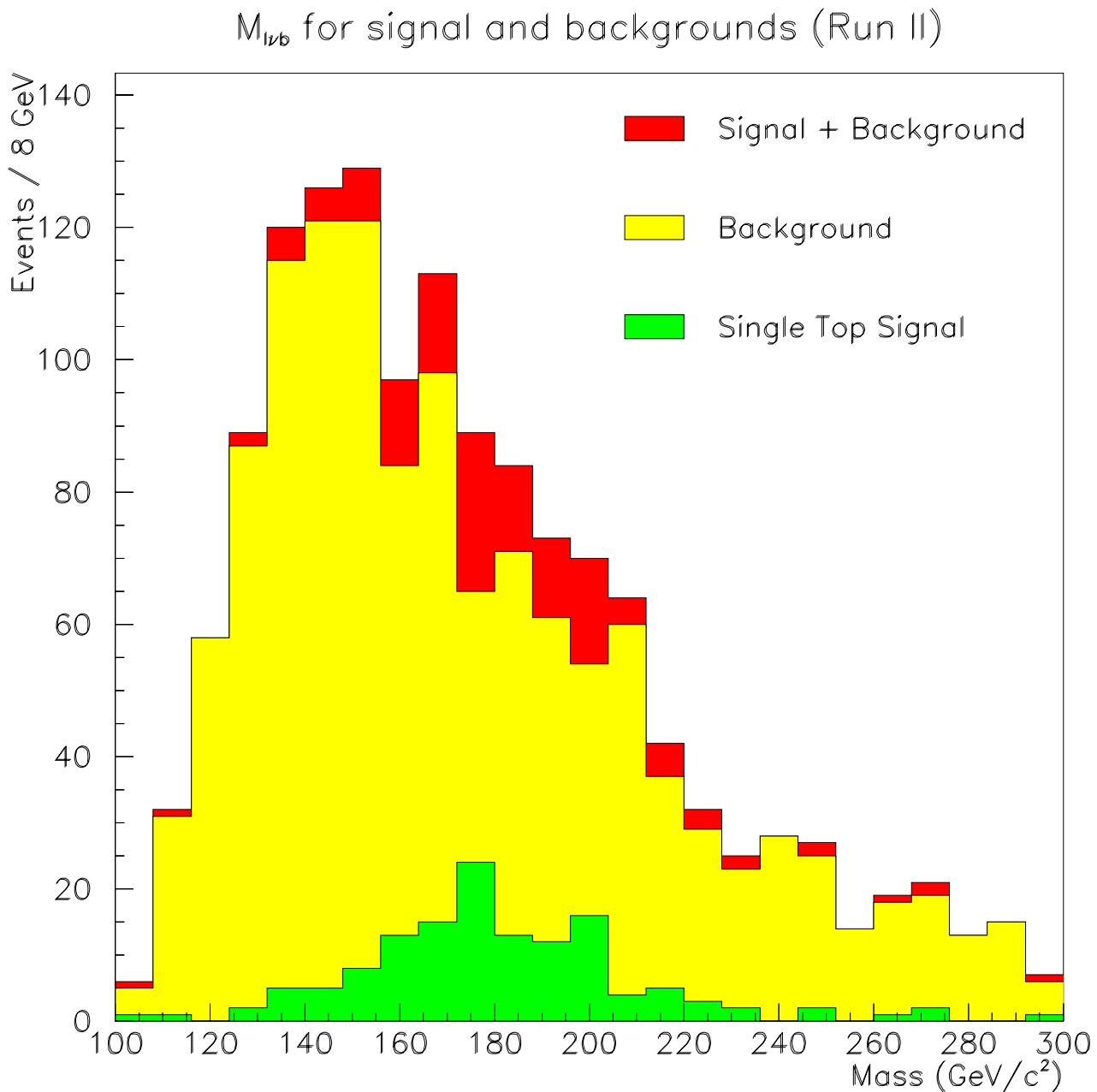
(Stelzer et al.)

$$\sigma(pp \rightarrow W^* \rightarrow t + X) = 0.88 \pm 0.05 \text{ pb}$$

(Smith et al.)

- * Provides direct access to t - W - b vertex
- * Top Quark Width $\Gamma(t \rightarrow X)$ and $|V_{tb}|$
 - Partial width from Single top cross section
$$\sigma(\text{single top}) \propto \Gamma(t \rightarrow W+b)$$
$$\sigma(q\bar{q} \rightarrow tb) \propto |V_{tb}|^2$$
- * Probe of anomalous couplings
 - large production rates
 - anomalous angular distributions

Single Top Production



- * Events with one lepton+ ≥ 2 jets (1 b-jet)
- * Expect ~ 150 events with S:B = 1:10 (2fb^{-1})
 - Challenging measurement...
 - More optimization needed e.g. H_T , $M(l\nu b)$

Rare Decays

Rare decays - SM and beyond

Within Standard Model

$t \rightarrow W b + g/\gamma$

$t \rightarrow W b + Z$ Near threshold

$t \rightarrow W b + H^0$ Might be beyond threshold

$t \rightarrow W + s/d$ Measure CKM matrix element

Beyond SM

Run II

$t \rightarrow c/\bar{u} + g/\gamma$ (FCNC) $< 1.4\% / 0.3\%$

$t \rightarrow c/\bar{u} + Z$ (FCNC) $< 2\%$

$t \rightarrow c/\bar{u} + H^0$ (FCNC)

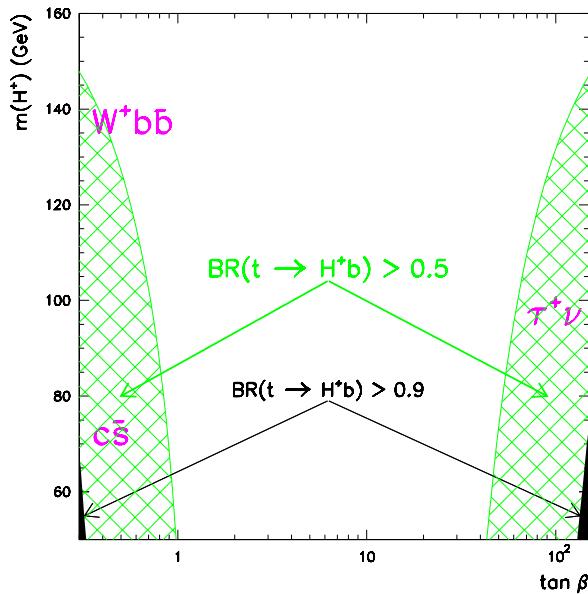
$t \rightarrow H^+ + b_{\tilde{t}}$ (SUSY) $< 11\%$
 $t \rightarrow \tilde{t} + \tilde{Z}$ (SUSY)

SM predicts branching fractions of FCNC decays $\sim 10^{-10}$

Observation of these decays would signal new physics

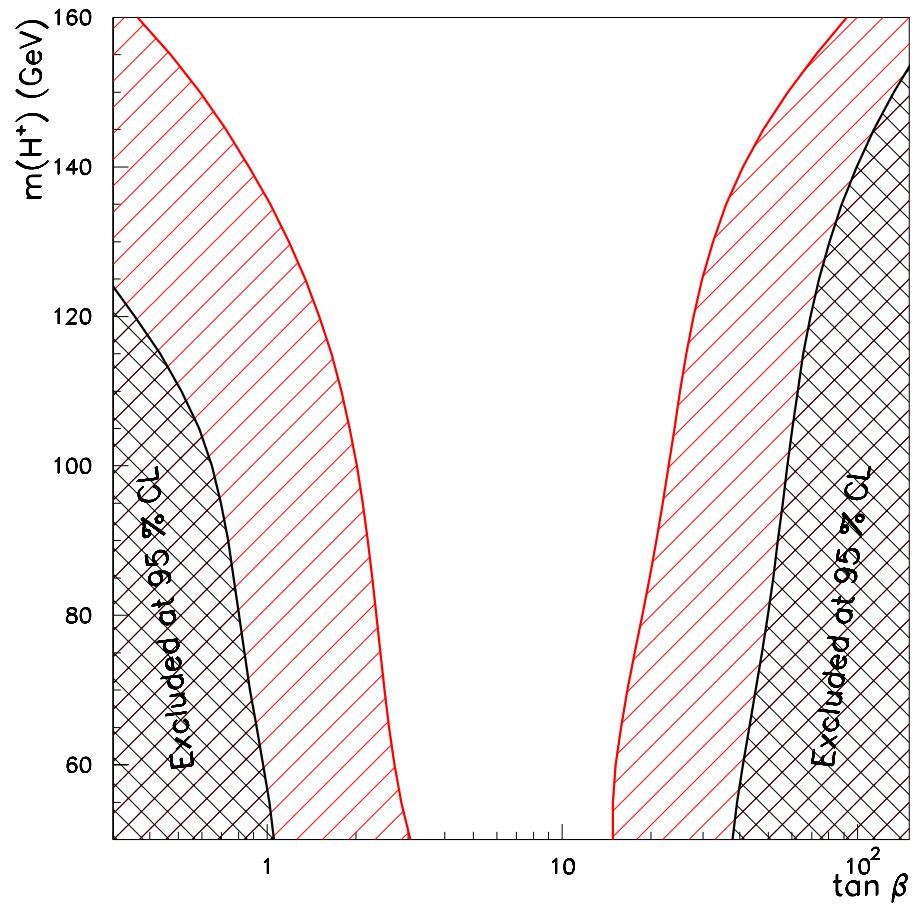
Charged Higgs Search

- * If $m(H^+) < m_t - m_b$ then $\Gamma(t \rightarrow H^+ b)$ can be large depending on $[m(H^+), \tan \beta]$



The parameter space

Expected
Run II exclusion
contours



Expected W, Z Event Yields

| <i>Channel</i> | <i>Run I (100pb⁻¹)</i> | <i>Run II (2fb⁻¹)</i> |
|--------------------------|-----------------------------------|----------------------------------|
| W \rightarrow ee | 60000 | 1.6M |
| W \rightarrow $\mu\nu$ | 40000 | 600000 |
| Z \rightarrow ee | 6000 | 160000 |
| Z \rightarrow $\mu\mu$ | 4000 | 50000 |
| W γ | 50 | 2000 |
| Z γ | 20 | 400 |
| WW,WZ,ZZ | a few | 150 |

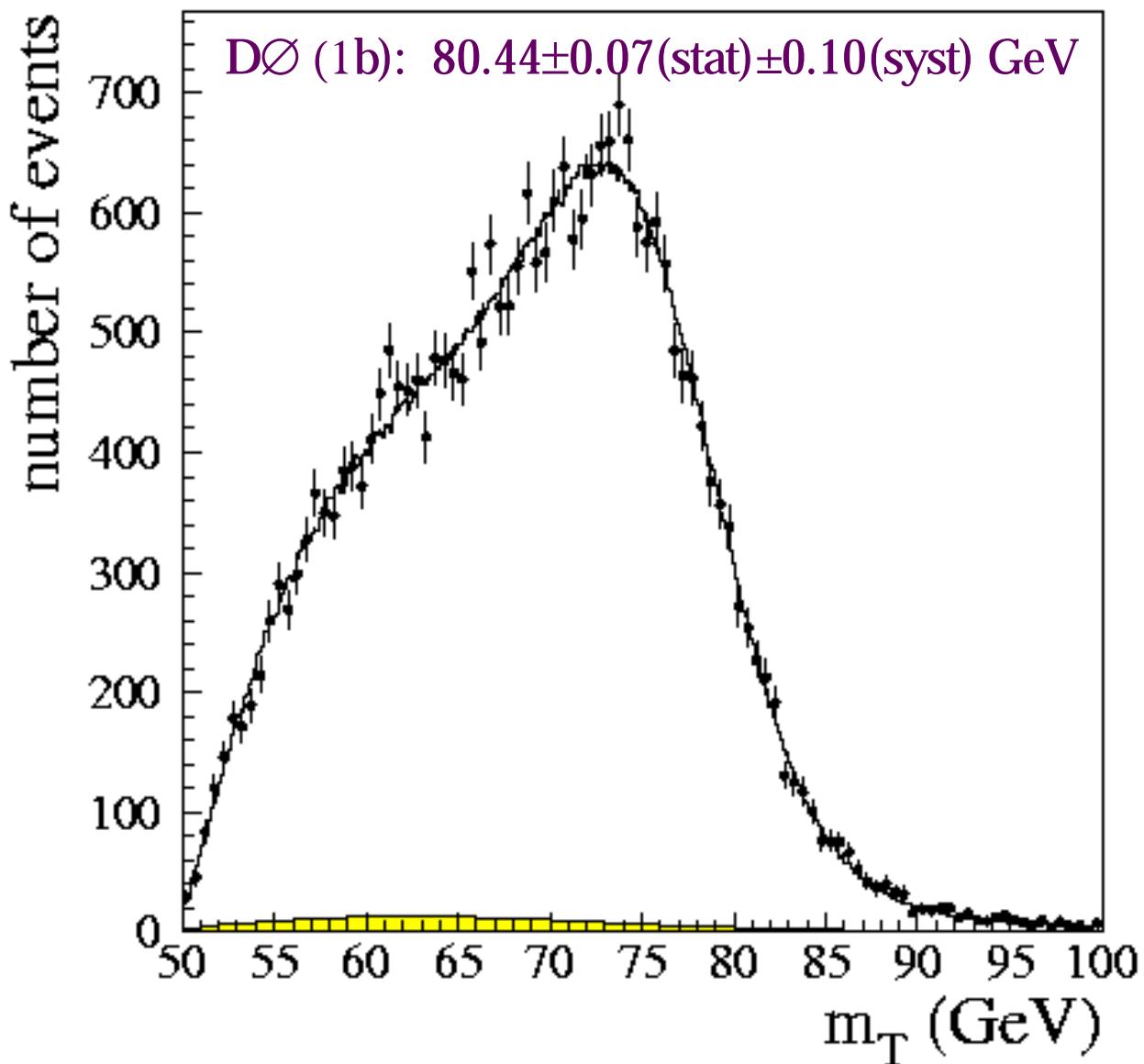
- * Increased luminosity
- * Increased c.o.m. energy ($\sqrt{s} = 1.8 \rightarrow 2.0 \text{ TeV}$)
 - cross section increases by 12%
- * Upgraded detectors
 - CDF:
 - better acceptance for e/ μ
 - addition of coverage for muon detectors
 - lower backgrounds for forward electrons
 - DØ:
 - better momentum measurement for muons
 - improved muon trigger
 - lower backgrounds for forward electrons

W Mass

- Measure W mass by fitting transverse mass spectrum

$$m_T = \sqrt{2 p_T^e p_T^\nu (1 - \cos\Delta\phi)}$$

→ Tevatron: $m_W = 80.41 \pm 0.09$ GeV



W Mass

- * Uncertainties from fit to m_T spectrum

| <i>source</i> | <i>Run I</i> (80 pb $^{-1}$) | <i>Run II</i> (2 fb $^{-1}$) |
|---------------------|----------------------------------|----------------------------------|
| statistics | 70 MeV | 17 MeV |
| lepton scale | 65 MeV | 16 MeV |
| resolution/response | 65 MeV | 16 MeV |
| W production/decay | 30 MeV | 15 MeV (?) |

- * Slower decrease than $1/\sqrt{N}$ due to pileup
(>1 interaction/crossing)
- * scale, resolution/response error constrained by control samples

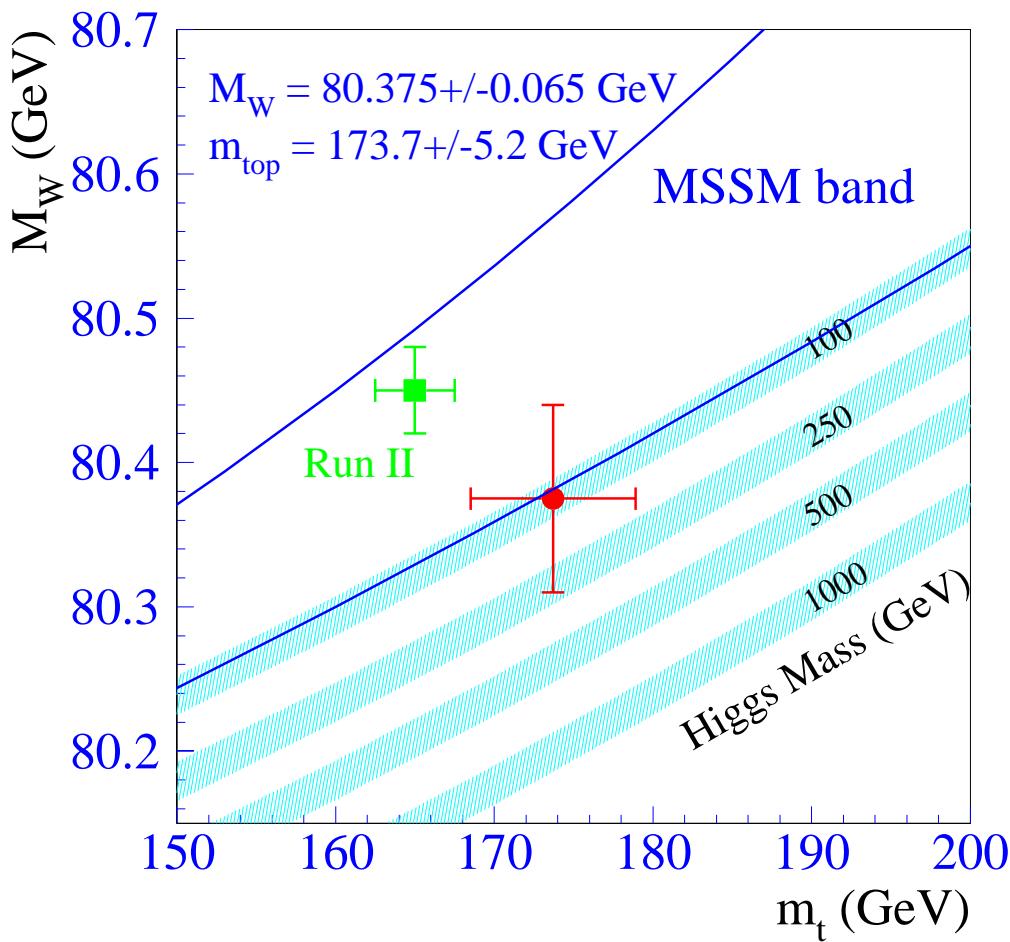
→ \propto statistical error

- * production, decay
 - need better calculations (theory), parton distribution functions
 - Total uncertainty ≤ 40 MeV (Run II)

W Mass vs Top Mass

- * m_t and m_H affect the SM prediction for m_W via radiative corrections
- * measure m_W and $m_t \rightarrow$ constrain m_H
- * for $\delta m_W = 40$ MeV and $\delta m_t = 2.5$ GeV constrain m_H to 80% precision

Compare: LEP II error on m_W is 40 MeV



W Width

- * Test for non-standard W decays/SM prediction for $\Gamma(W \rightarrow l\nu)$

→ Cross section ratio:

$$R = \frac{\sigma(p\bar{p} \rightarrow W) \cdot B(W \rightarrow l\nu)}{\sigma(p\bar{p} \rightarrow Z) \cdot B(Z \rightarrow ll)}$$

$$B(W \rightarrow l\nu) = R \frac{B(Z \rightarrow ll)}{\sigma(p\bar{p} \rightarrow W) / \sigma(p\bar{p} \rightarrow Z)}$$

$$\Gamma_W = B(W \rightarrow l\nu) \cdot \Gamma(W \rightarrow l\nu)$$

$$\Rightarrow \Gamma_W = 2.062 \pm 0.059 \text{ GeV (D}\emptyset\text{+CDF)}$$

☺ insensitive to multiple interactions

☹ limited by pdf uncertainty in σ_W/σ_Z
calculation to $\approx 1\%$

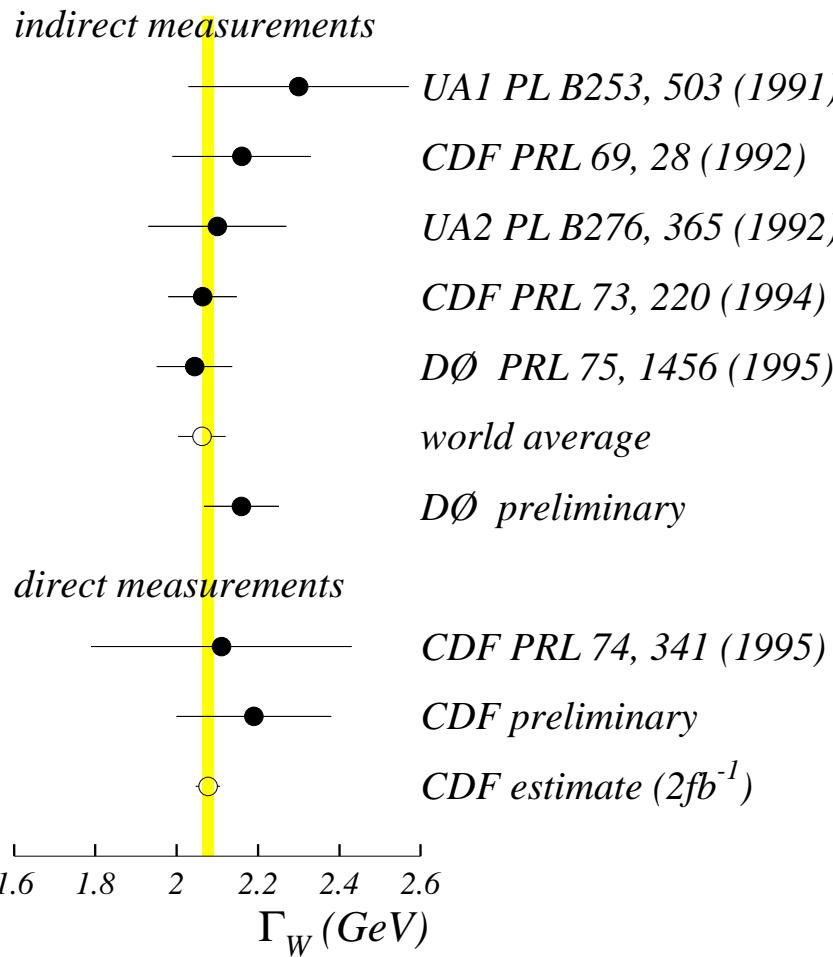
W Width

→ Tail of m_T spectrum:

$$\Rightarrow \Gamma_W = 2.19 \pm 0.19 \text{ GeV (CDF)}$$

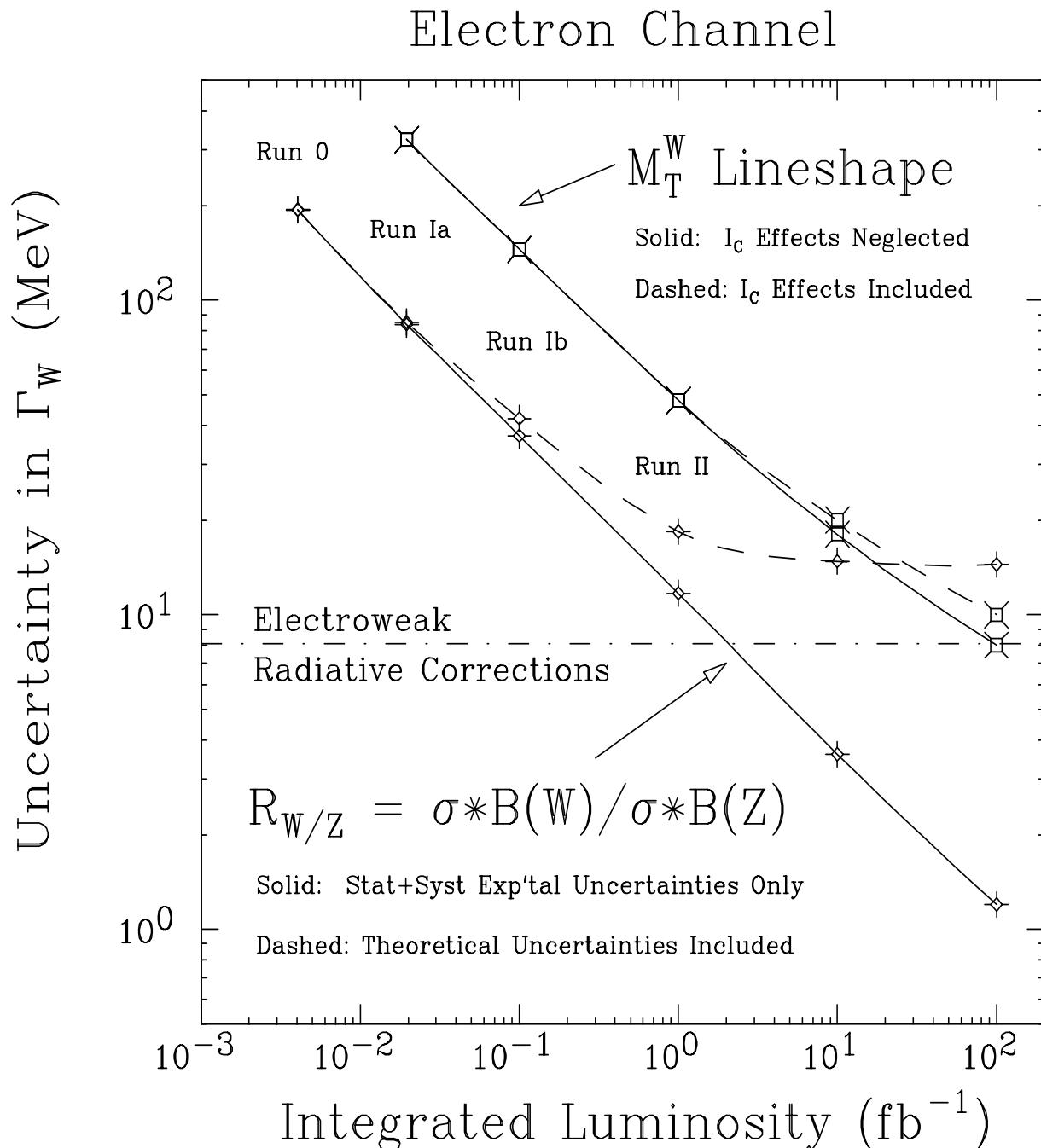
- ☺ no theoretical limitations
- ☺ statistical uncertainty dominates
- ☹ sensitive to multiple interactions

⇒ Expect 30 MeV uncertainty for 2 fb^{-1}



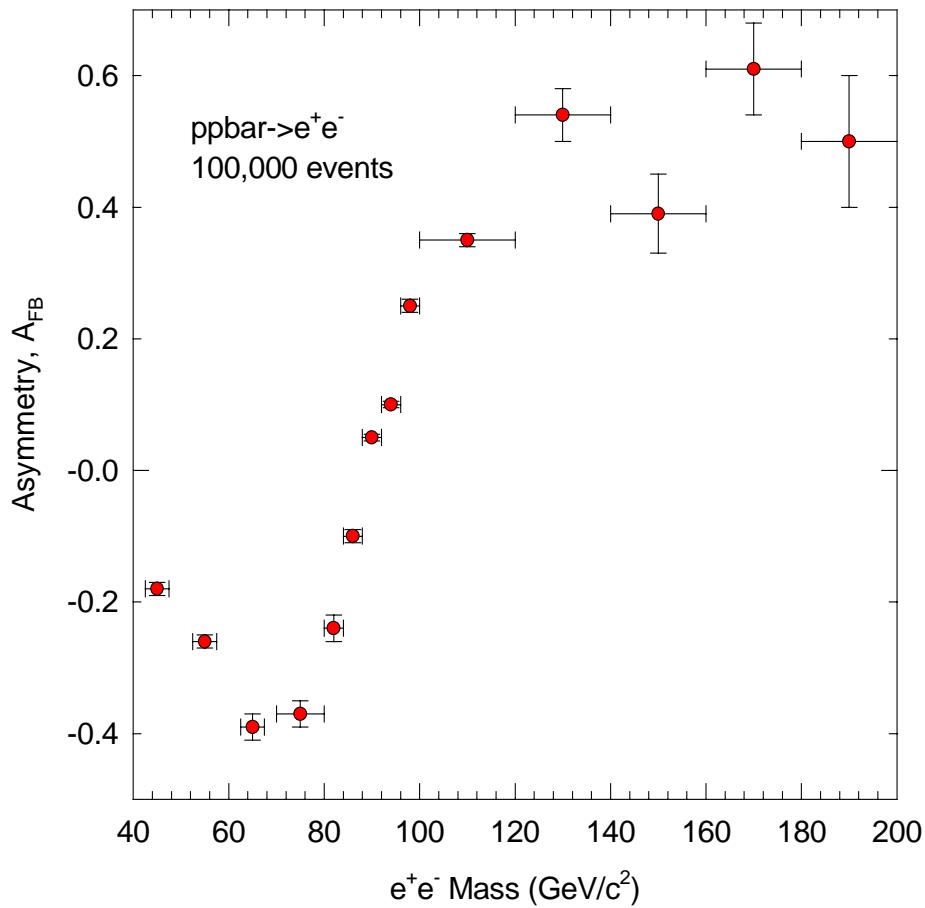
W Width

- * Expected uncertainty vs integrated luminosity



Z Charge Asymmetry

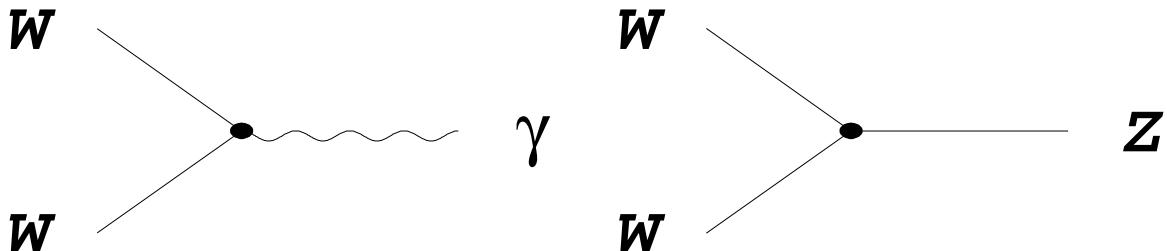
- * Forward-backward asymmetry in leptons from Z decays ($q\bar{q} \rightarrow \ell^+\ell^-$)
 - depends on vector and axial couplings of Z to quarks and leptons \Rightarrow sensitive to $\sin^2\theta_W$
 - systematic errors small
 - probe of exotic physics (Z')



- * $2 \text{ fb}^{-1} \Rightarrow 160k \text{ Z} \rightarrow ee \text{ events}$
- * Measure $\sin^2\theta_W$ to 0.001 (LEP 0.0016)

WW γ and WWZ Couplings

- * Follow from the gauge structure of the SM



4 independent amplitudes with coupling constants

$$\kappa = 1, \quad \lambda = 0$$

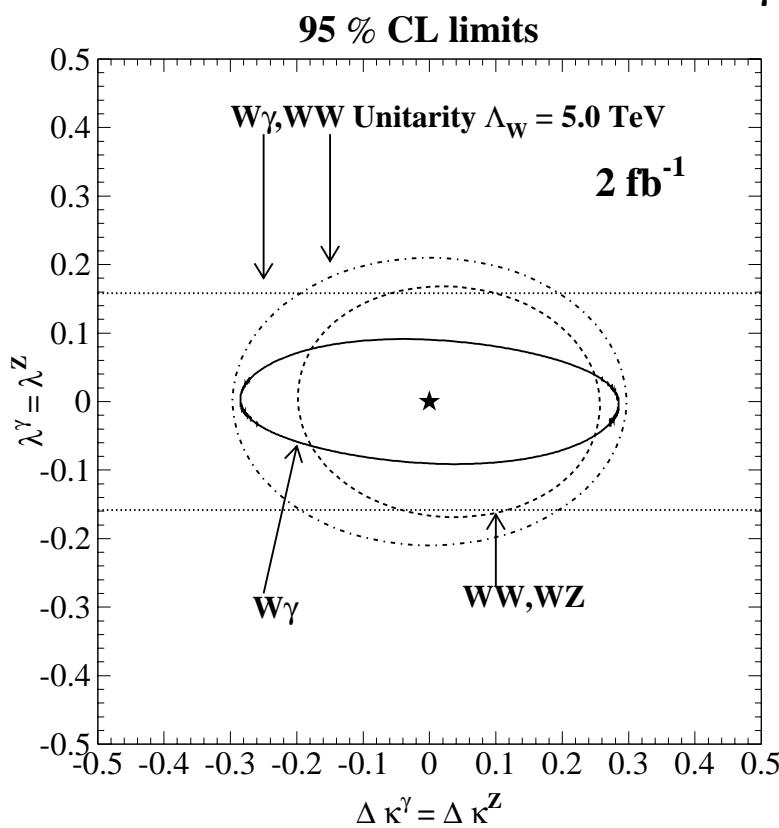
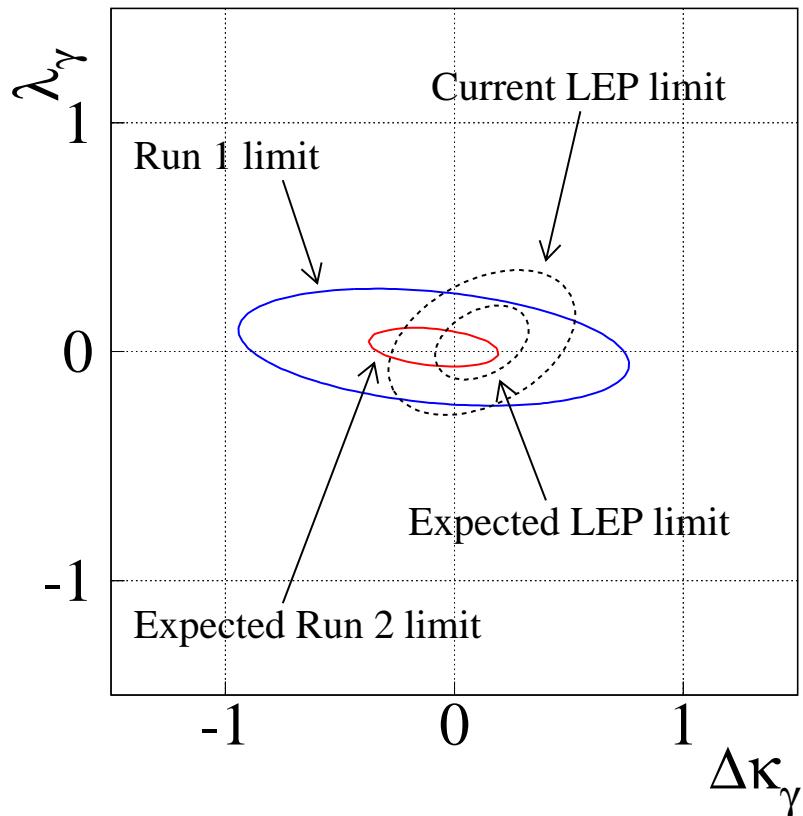
$$\underbrace{\kappa = 0, \quad \lambda = 0}_{CP}$$

- * Limits on $WW\gamma$, WWZ couplings (95% CL)

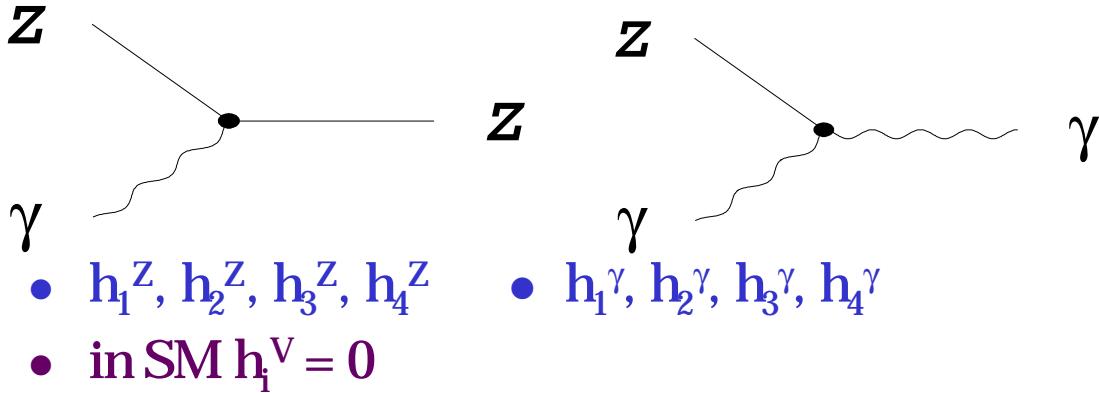
| channel | present limits (DØ) | 1 fb^{-1} |
|----------------------------------|--|---------------------|
| $W\gamma \rightarrow l\nu\gamma$ | $-0.93 < \Delta\kappa_\gamma < 0.94$ | < 0.38 |
| | $-0.31 < \lambda_\gamma < 0.29$ | < 0.12 |
| $WW, WZ \rightarrow l\nu jj$ | $-0.47 < \Delta\kappa_\gamma < 0.63$ | < 0.35 |
| | $-0.36 < \lambda_\gamma < 0.39$ | < 0.19 |

\Rightarrow Limits a factor of 2-3 better in Run II

WW γ and WWZ Couplings

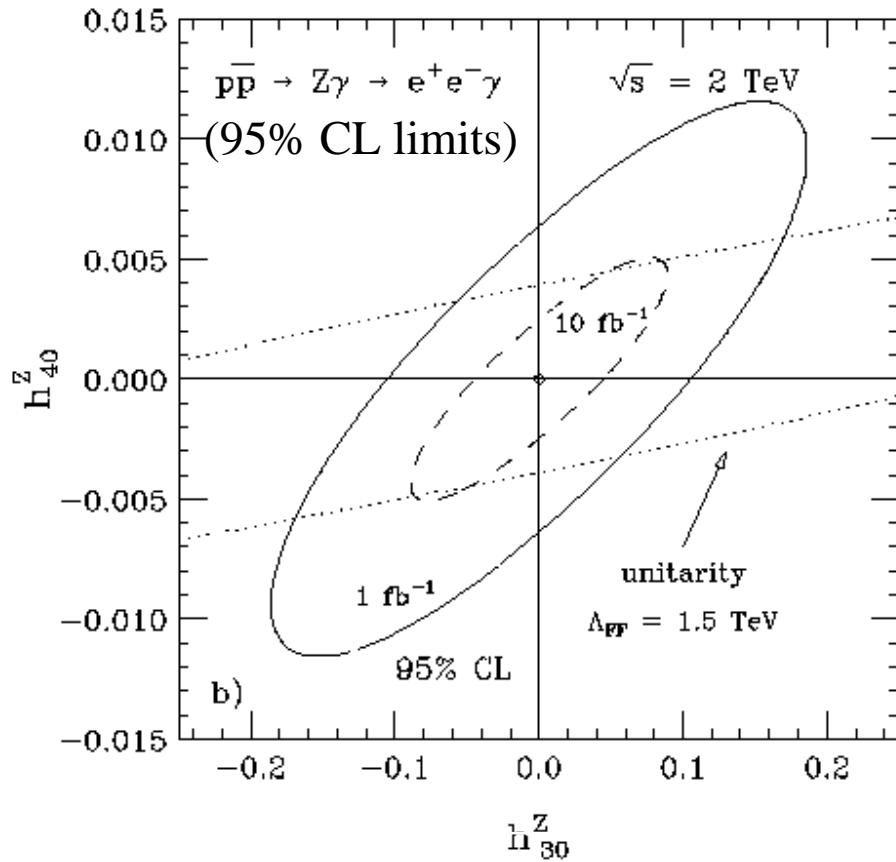


ZZ γ and Z $\gamma\gamma$ Couplings



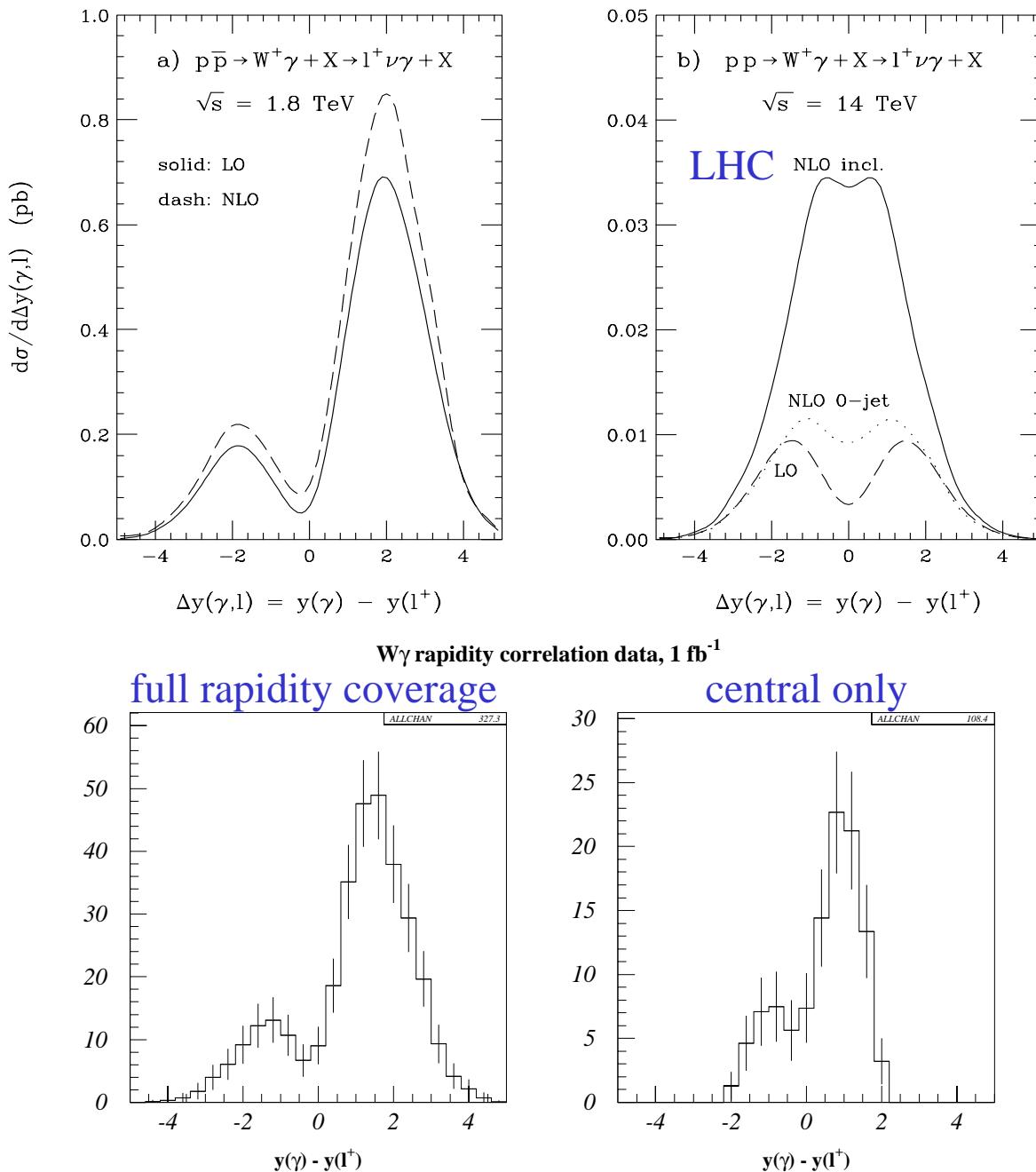
| | Run I | Run II | Run I | Run II |
|--------------------------------|-------------------|---------------|--------------------|---------------|
| $Z\gamma \rightarrow ll\gamma$ | $ h_{3,1} < 1.6$ | < 0.11 | $ h_{4,2} < 0.4$ | < 0.0064 |
| $Z\gamma \rightarrow vv\gamma$ | $ h_{3,1} < 0.9$ | < 0.038 | $ h_{4,2} < 0.21$ | < 0.0027 |

- Limits a factor of 10-100 better in Run II (1fb $^{-1}$)



Radiation Zero in $W\gamma$ Production

- * all amplitudes for $q\bar{q} \rightarrow \gamma W$ vanish for $\cos\theta^* = \pm 1/3$
- * observe via $l-\gamma$ rapidity difference



Conclusions

- * Run II is scheduled to begin in April 2000
 - * expect $\geq 2 \text{ fb}^{-1}$ ($20 \times$ Run I)
 - * upgraded detectors
 - * top quark physics:
 - tt cross section
 - top quark mass
 - tt resonances
 - Wtb vertex
 - spin correlations
 - observation of single top production
 - * gauge boson properties
 - W mass
 - W width
 - Z charge asymmetry
 - trilinear couplings
 - constrain Higgs mass
- } standard model top?

Top Physics

Top quark properties

- * Production cross section, dynamics
- * Branching ratios, rare decays
- * t-W-b vertex
- * Top quark width
- * Top quark mass

$|V_{tb}|$

- * $|V_{tb}|$ expected to be close to 1 (≥ 0.998), assuming 3 generations
- * If 4th generation exists \Rightarrow no constraints
- * Any departure of $|V_{tb}|$ from 1 \rightarrow indication of non standard physics

$$\frac{B(t \rightarrow W + b)}{B(t \rightarrow W + q)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

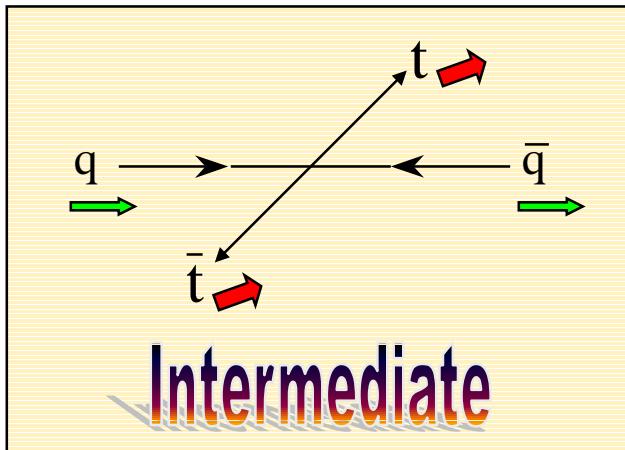
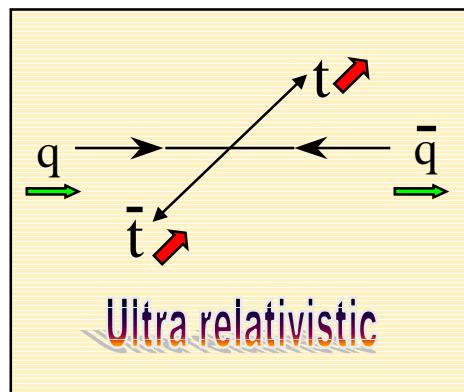
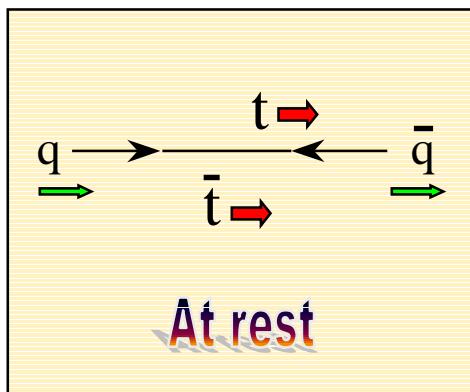
- * use b-tagging in tt decays
 - single tags/ double tags in l+jets and dilepton
 - no-tags/single tags in l+jets and dilepton
 - number of tags in dilepton events
 - double tag one jet/ tag both jets
- * Run II projections

$$\delta V_{tb} \approx 2\% \quad (2 \text{ fb}^{-1})$$

benefits from improvements in b-tagging efficiency and reduced systematic error on b-tagging

t̄t Spin Correlation

- * Significant asymmetry exists in same-spin vs. opposite-spin top quark pairs
 - expect 70% t̄t opposite helicity
- * Polarization state is transmitted to the angular distribution of decay products.
- * Non-zero measurement
 - Confirms top quark spin = 1/2
 - ⇒ set lower limit on top quark width
 - ⇒ probe presence of non-standard interactions

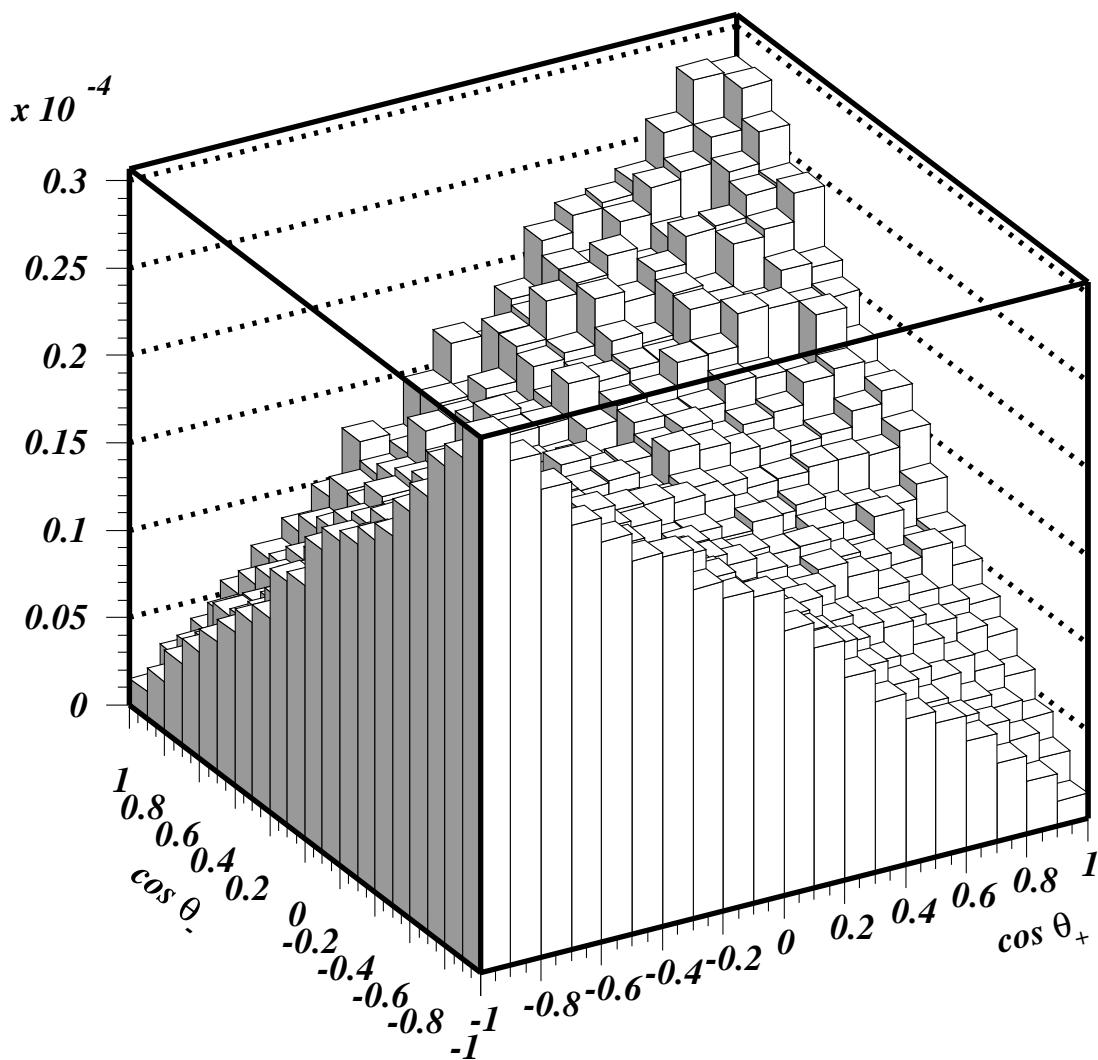


Optimal spin quantization
basis: Off-diagonal

Only like-spin combinations
are produced

t̄t Spin Correlation

- * Use charged lepton, lightest quark angular distributions in lepton+jet events
 - difficult to identify the down quark jet.
- * OR, angular correlation of leptons in dilepton events.
 - Possible to measure $\approx 3 \sigma$ effect in 2fb^{-1}



Gauge Boson Properties

- * W Boson Mass
- * W Boson Width
- * W and Z Asymmetries
- * Trilinear Gauge Boson Couplings

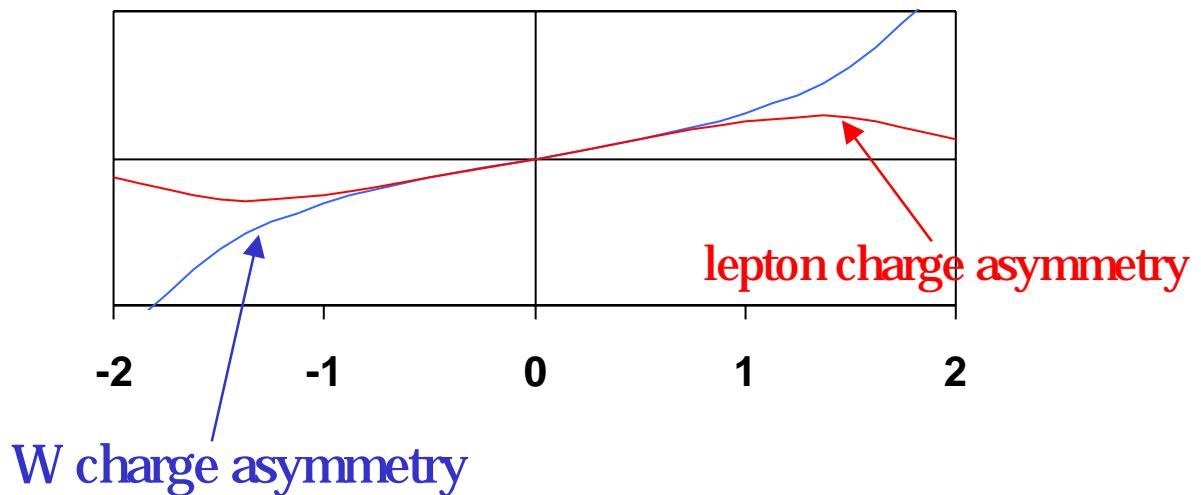
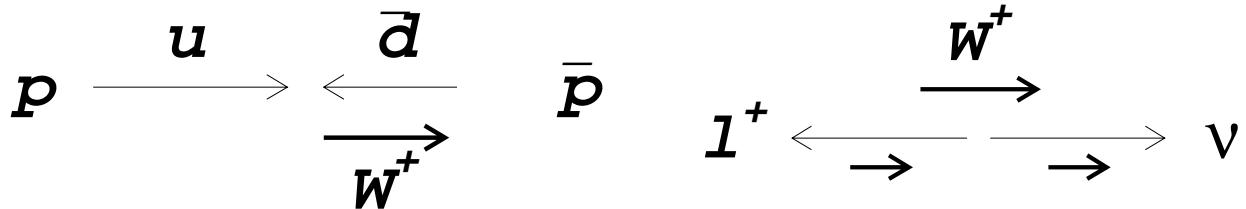
W Mass

- * Other techniques:

- fit electron p_T spectrum
 - ☺ insensitive to missing p_T measurement (pileup)
 - ☹ sensitive to W production, decay model
- use ratio of electron p_T or m_T for W and Z decays
 - ☺ can be calculated perturbatively
 - ☺ less sensitive to W production, decay model
 - ☹ statistical uncertainty dominated by Z sample
- fit electron energy spectrum
 - ☺ insensitive to missing p_T measurement (pileup)
 - ☹ sensitive to longitudinal momentum

W Charge Asymmetry

- * Lepton charge asymmetry in W decays
 - production: $\langle x_u \rangle > \langle x_d \rangle$
 - decay: V-A



lepton $|\eta|$
coverage out to
2.0 essential

